Where and How Does MiniBooNE Get its Protons?

(It's a mystery!)

Peter Kasper

The Fermilab Accelerator Components

- Preaccelerator
  - ➪ H- ions from 0 to 750 keV
- Linac
  - ➪ H- ions from 0.75 to 400 MeV
- Booster
  - ➪ Protons from 0.4 to 8 GeV
  - ➪ Beam to MiniBooNE
- Will not discuss the other accelerators:-
  - ➪ Main Injector: 8 - 120 GeV (and Recycler storage ring)
  - ➪ Tevatron: 0.12 - 0.98 TeV
  - ➪ Antiproton Source (and Accumulator storage ring)

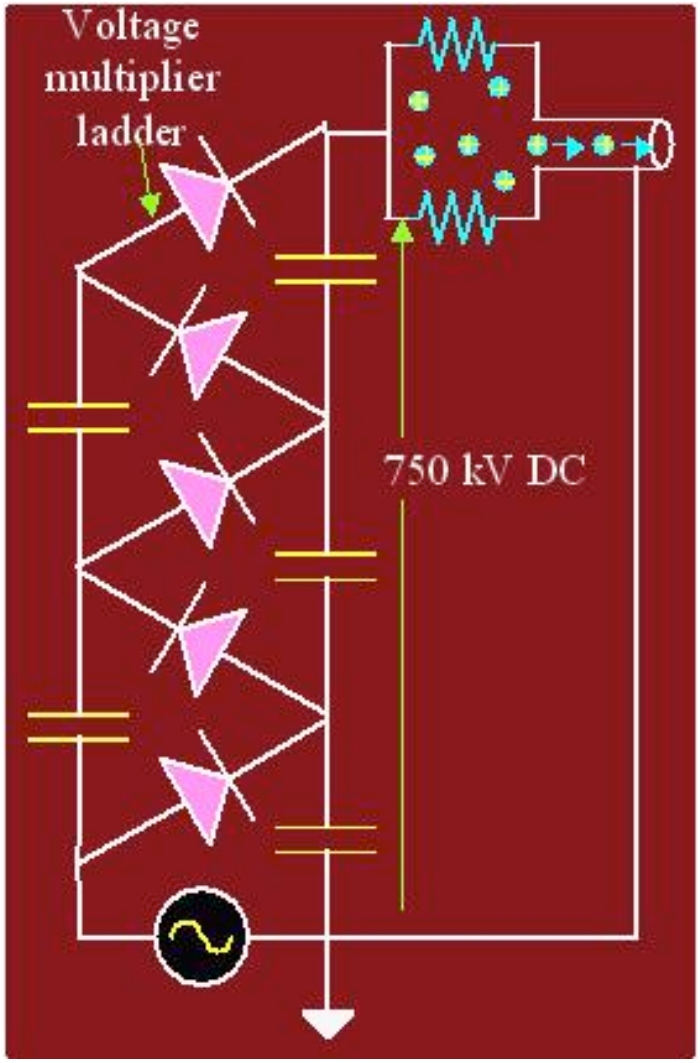
The Fermilab Accelerator Complex

PROTON SOURCE DEPARTMENT

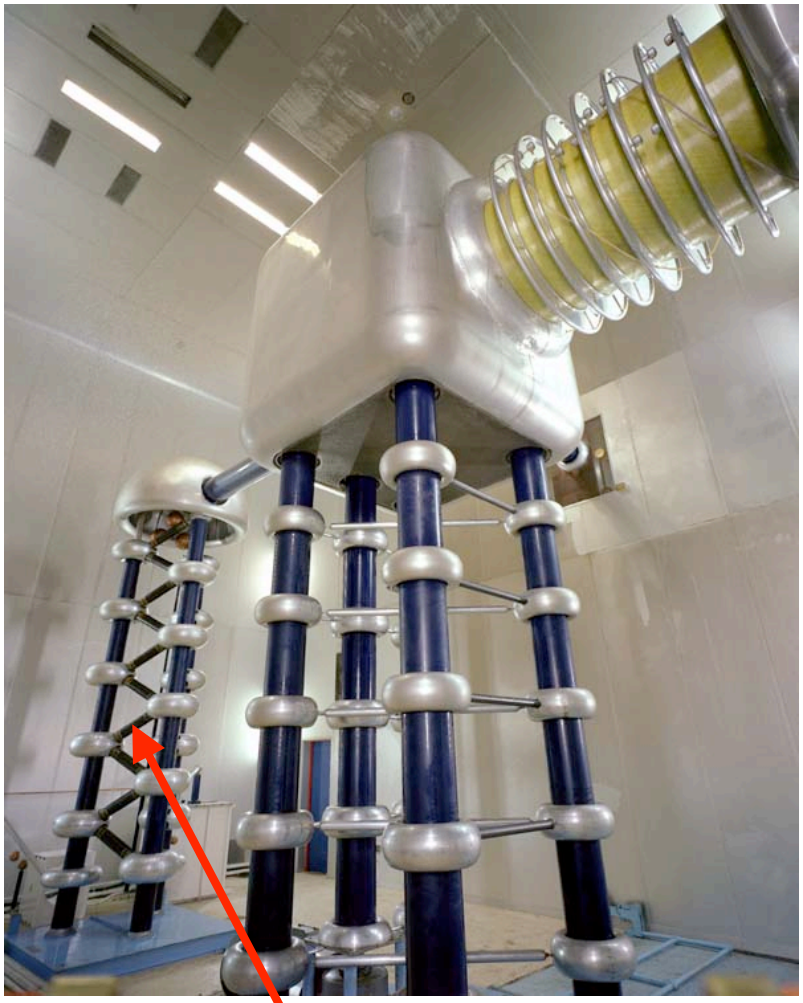
The Preaccelerator

- Consists of a source housed in an electrically charged dome .. The Cockcroft-Walton
- The source converts H_2 gas to H^- ions
- 480 V ac current and a series of capacitors and diodes is used to charge the dome to -750 keV

The ionized gas is accelerated through a column from the charged dome to the grounded wall.



The Cockcroft-Walton Preaccelerator

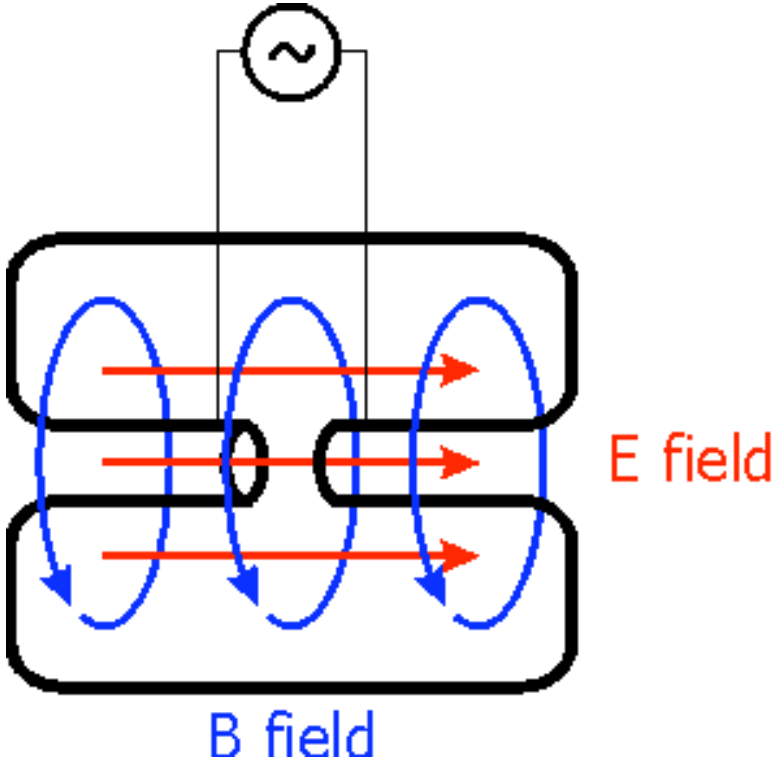


Diodes

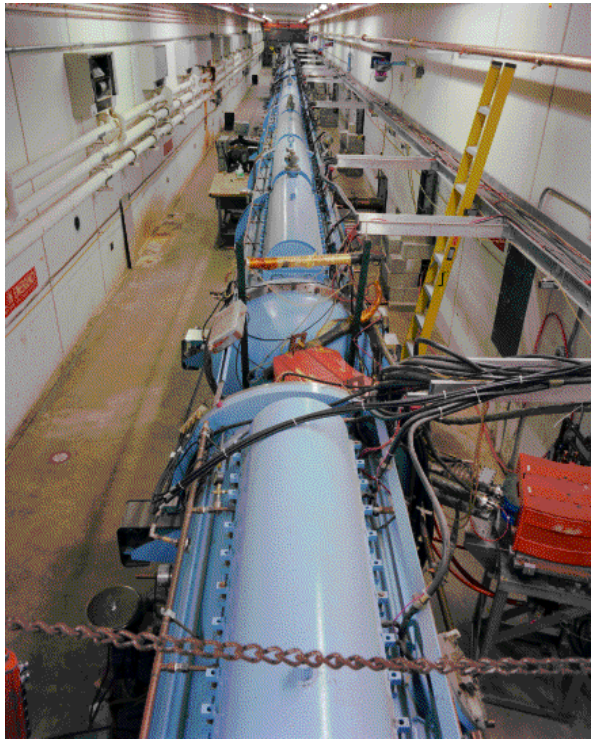
The H_2 Bottle

The Linac: a Series of RF Cavities

- An applied AC current induces an oscillating magnetic field which in turn induces and oscillating electric field
- The cavity acts as an LCR circuit and hence has a well defined resonant frequency
  - ➪ Noise is thereby suppressed

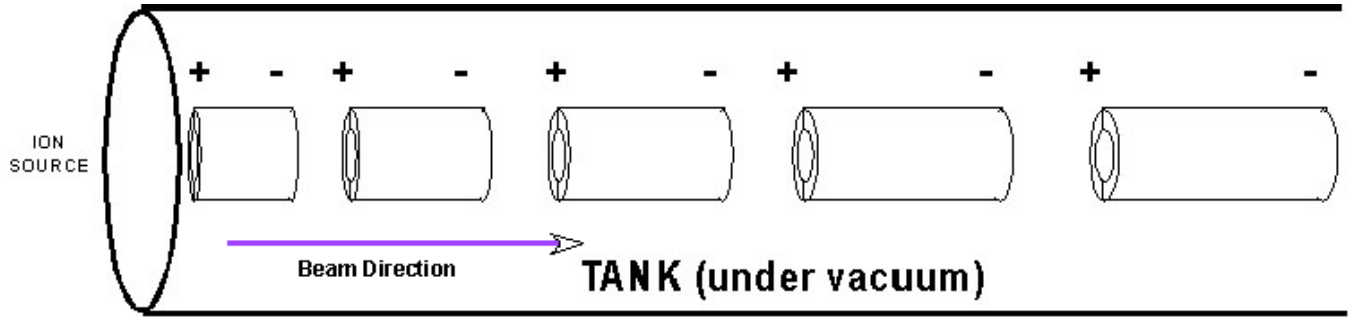


The Linac: 0.75 - 200 MeV



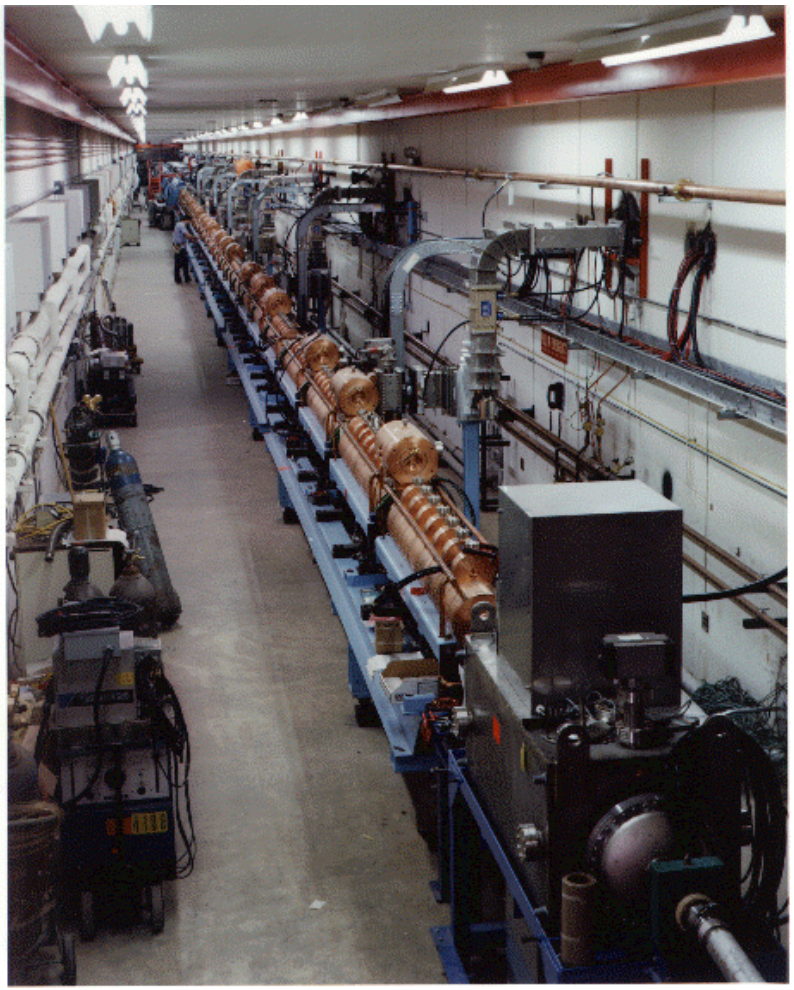
Outside

Inside



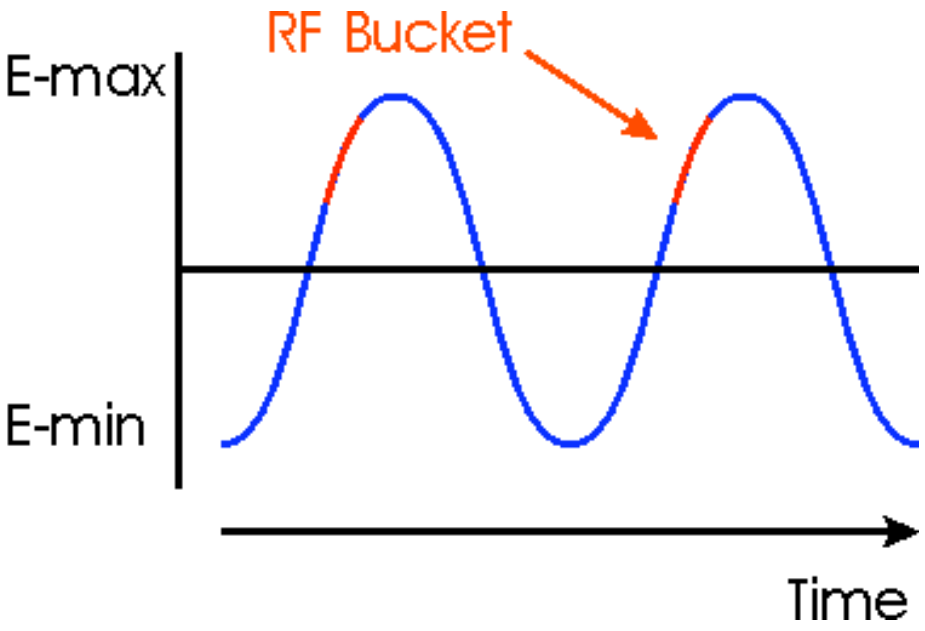
The Linac: 200 - 400 MeV

- Low energy Linac RF is 201 Mhz
- High energy Linac RF is 805 MHz
- The gap spacings vary so that the "nominal" particle is inside each successive gap at the same point on the RF phase curve
- Optimal phase region is < E-max
  - ➪ Fast particles arrive early and see less field
  - ➪ Slow particles arrive late and see higher field
  - ➪ Beam becomes bunched



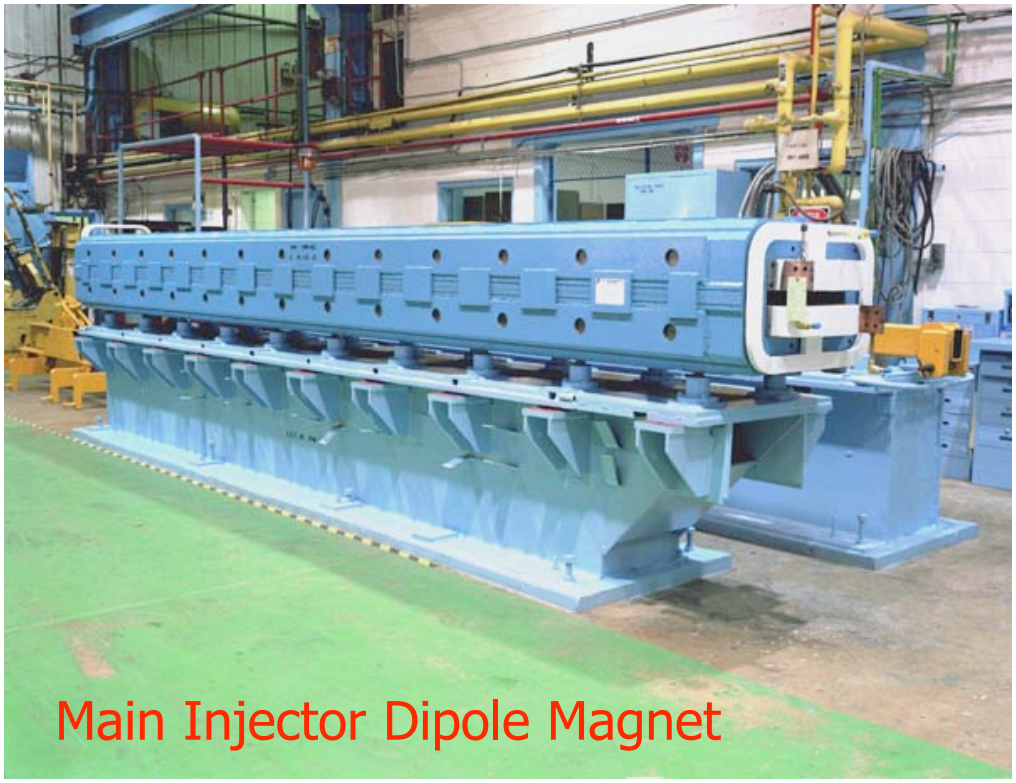
Buckets and Bunches

- The part of the RF phase curve in which particles will be accelerated is called an RF bucket
- Only particles in synch with the RF buckets will be accelerated
- The particles in an RF bucket is called a bunch



Magnets: How We Control Beams

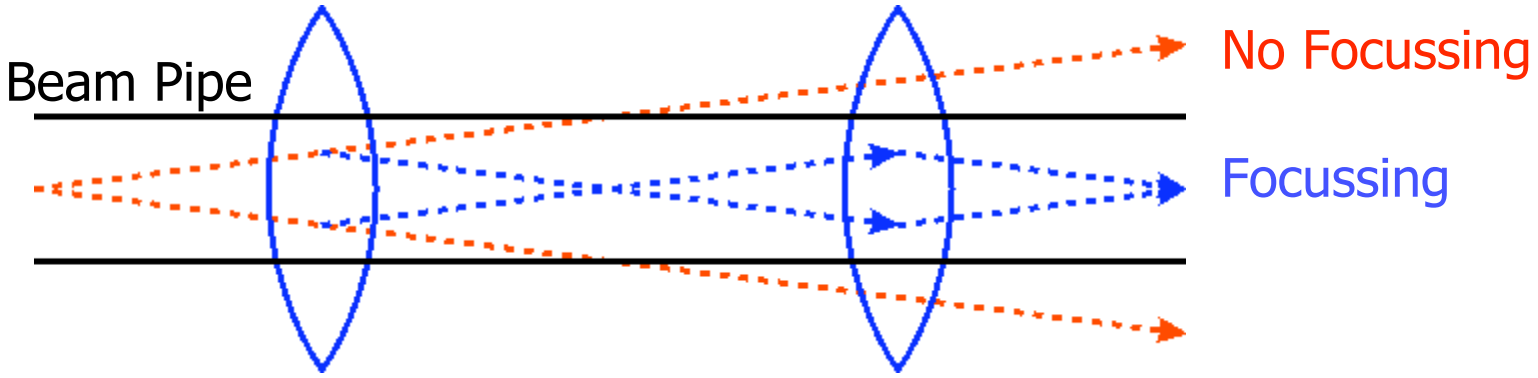
- Beams are transported through vacuum beam pipes with the aid of magnet strings which steer the beam and keep it inside the pipe.
- Dipole Magnets
  - Uniform field B perpendicular to beam direction Bends beam in an arc of radius R = P/B
  - P is beam momentum
  - B is field strength



Main Injector Dipole Magnet

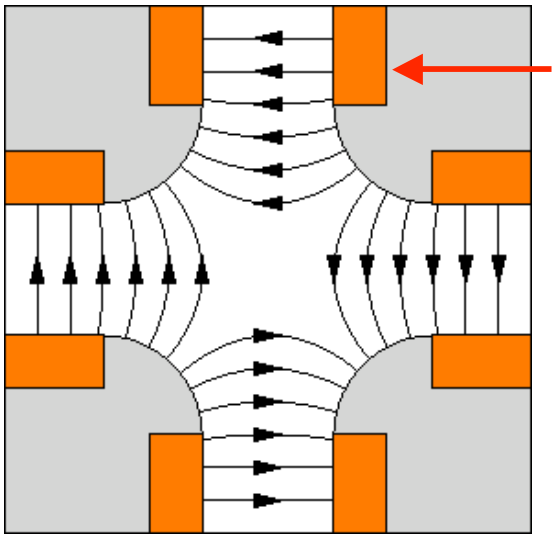
The Need for Focussing

- Accelerators and beam lines with only dipole magnets don't work
- Perturbations to a beam particle's direction or momentum from the nominal will cause the particle to eventually be lost
  - ➪ e.g. any small vertical component to its motion will cause it to drift up (or down) until it hits the beam pipe.
- Booster beam does 4000 circuits = 1.9 km & pipe radius is 5 cm therefore beam would need to be collinear to < 0.025 □-radians
- Quadrupole Magnets provide focussing similar to optical lenses

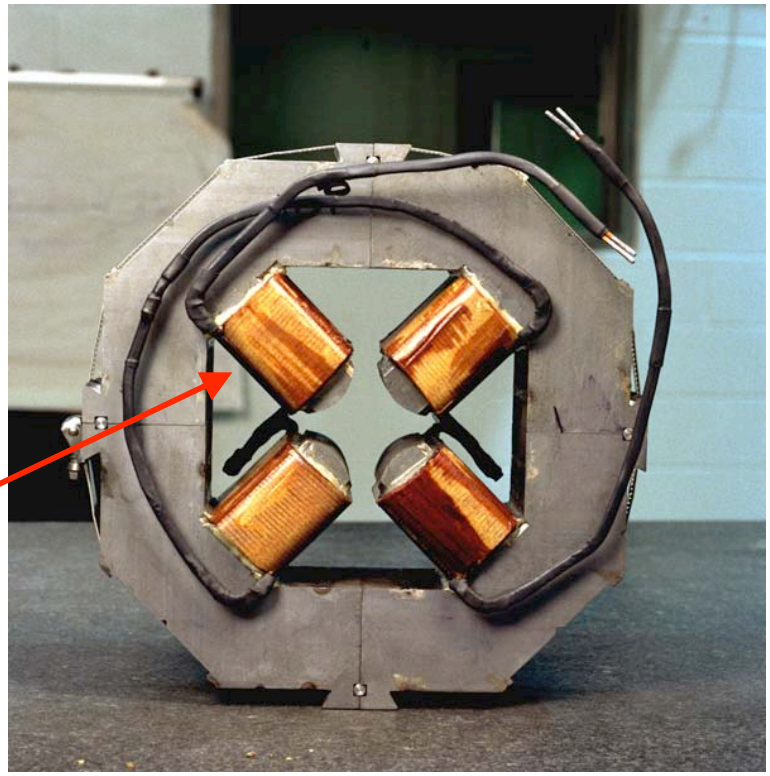


Quadrupole Magnets

- Field strength varies linearly with vertical or horizontal displacement from beam center.
  - ➪ Horizontal focussing implies vertical defocussing
  - ➪ Magnet pairs of opposite polarity give net focussing



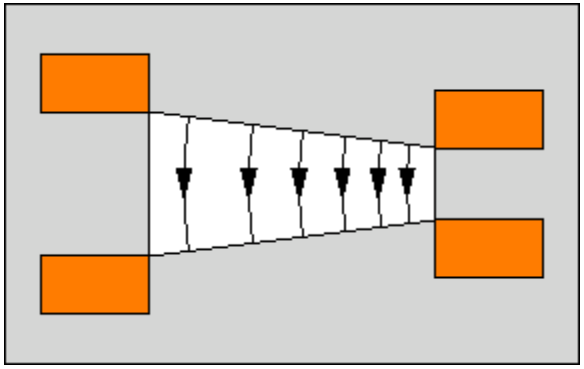
Coils



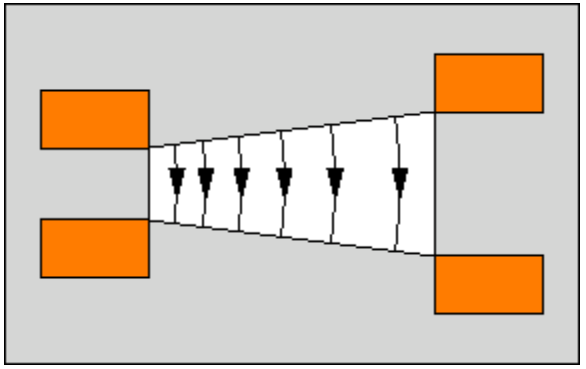
Linac Quadrupole Magnet

Combined Function Magnets

- The main Booster magnets are combined function
  - The resulting fields are a linear combination of a dipole field and a quadrupole field.
  - Relative quadrupole/dipole strengths are defined by the angle of the wedge shaped aperture



Horizontally focussing

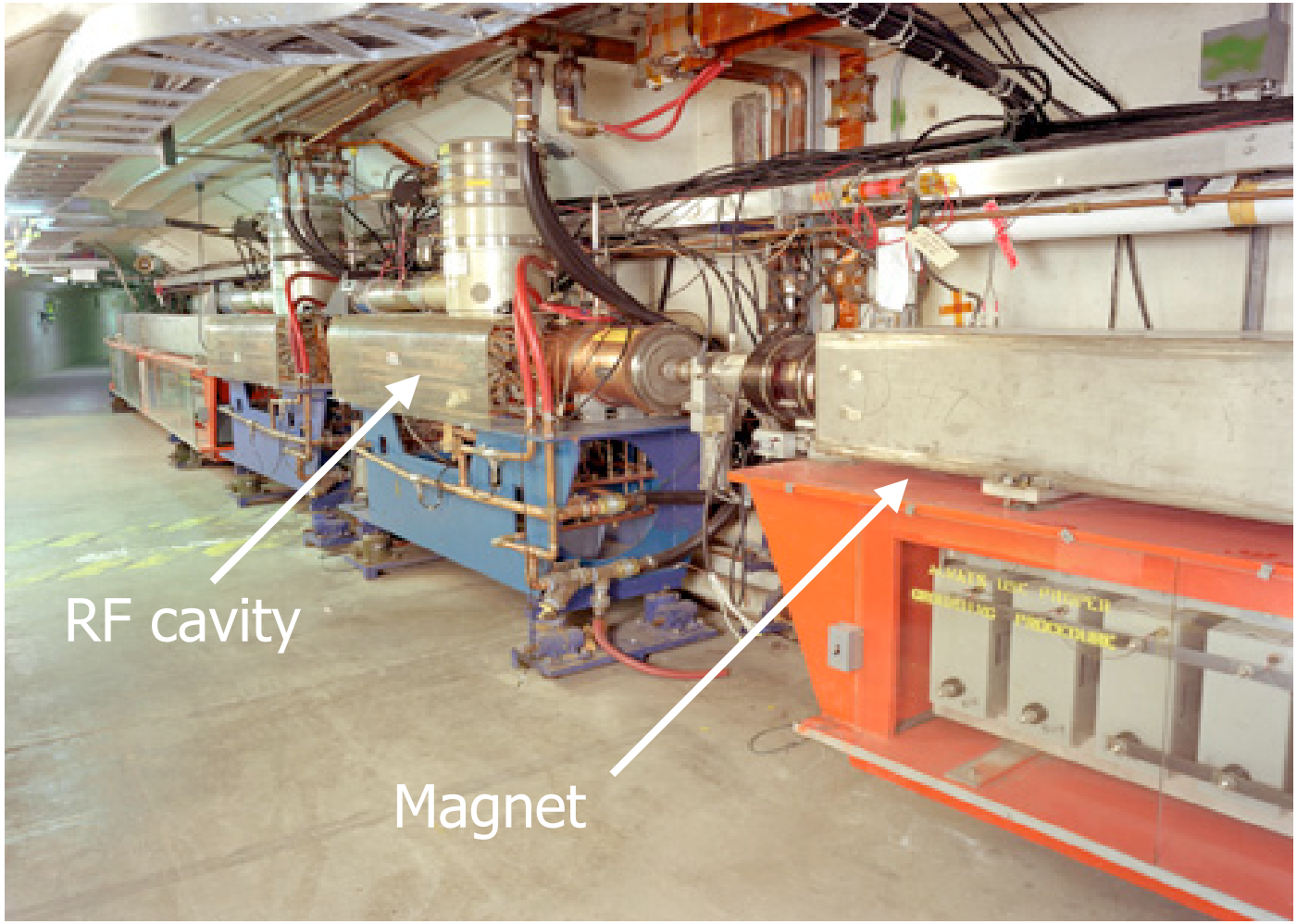


Horizontally defocussing

The Booster

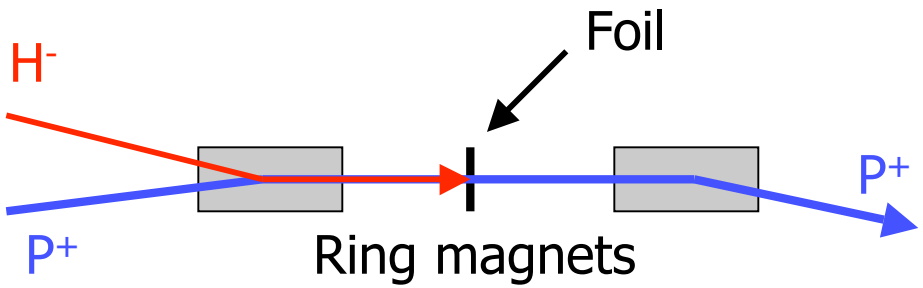
- Consists of a series of magnets and RF cavities arranged in a circle 75.5 meters in radius
- The magnets keep the beam circulating around the ring while the RF cavities accelerate it.
  - Initial: K.E. = 0.4 GeV, v = 0.713 c
  - Final: K.E. = 8 GeV, v = 0.994 c
  - RF varies from 37.8 to 52.8 MHz as v increases
- A Booster batch:
  - Length (time): T = 2□ * 75.5 / (0.994 c) = 1.6 □s
  - # Bunches: T/(52.8*1E6) = 84 = harmonic number

Inside the Booster Tunnel

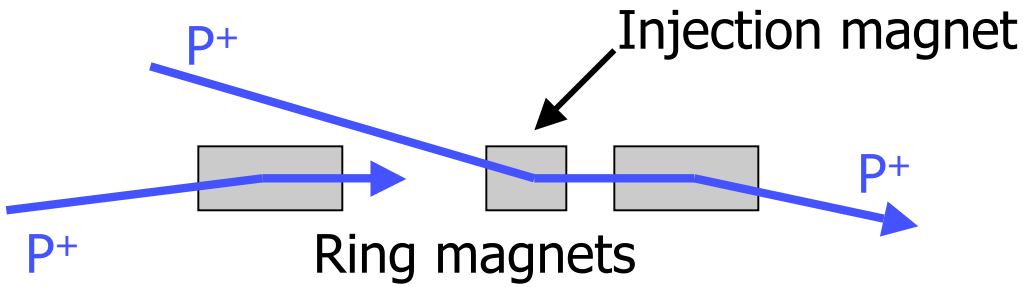


Getting the Beam into the Booster

- Why does the Linac accelerate H^- ions whereas all the other machines accelerate protons?
  - ➪ Multiple Booster turns worth of Linac beam can be injected simultaneously
    - ➔ Higher beam intensities



Stripping foil converts H^- ions to protons.



Injection magnet has to turn off before beam completes one full turn

The Acceleration Process

- The Booster has 96 main bending magnets each of which bends the beam by 360/96 = 3.75 degrees
  - Low power "trim" magnets are used to make corrections to the beam orbit.
- B field increases as P increases
  - The main Booster magnets form part of an LCR circuit which resonates at 15 Hz
  - Magnet current varies sinusoidally
  - Time between booster pulses is 1/15 = 67 msec
  - Linac beam is injected into the Booster at the bottom of the sine wave and extracted 33.3 msec later

The Acceleration Process II

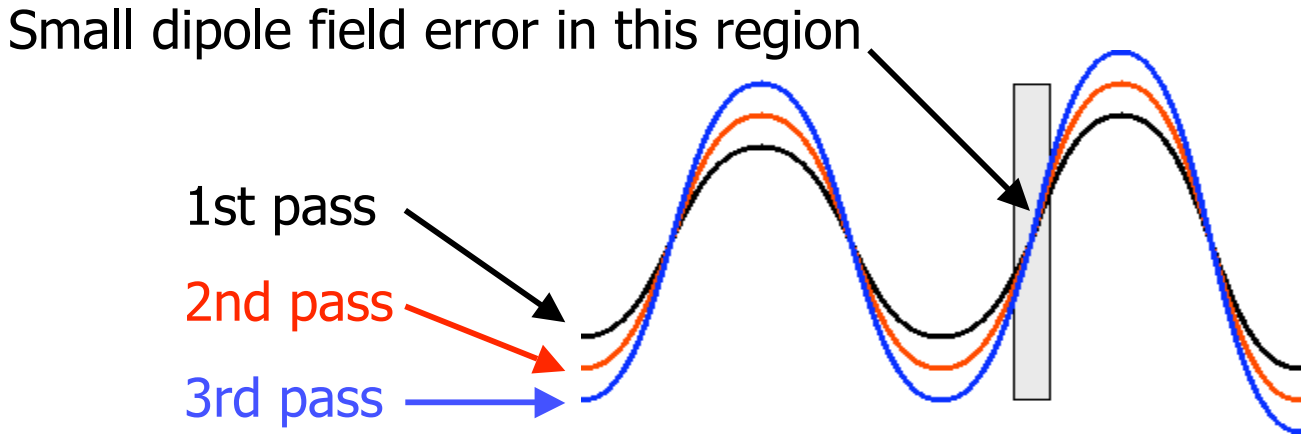
- The rate of increase in beam momentum has to match the increase in the magnet field strength
- The voltage applied to the RF system varies through the ramp in order to ensure P/B remains constant
  - ➪ A feedback system is used to do this (RPOS)
  - ➪ The horizontal beam position is measured at some convenient point in the ring
  - ➪ The RF voltage is adjusted such that the beam is held fixed at that point
    - ➔ Voltage is increased if the beam drifts inwards
    - ➔ Voltage is decreased if the beam drifts outwards

Betatron Oscillations

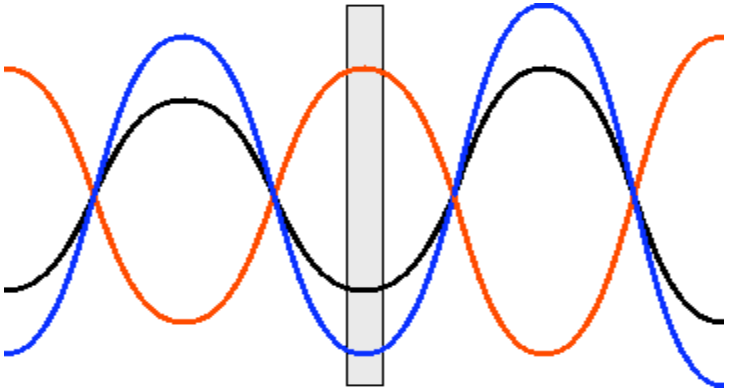
- The quadrupole magnets cause beam particles to oscillate about the nominal beam orbit
- The number of oscillations that a particle undergoes in one turn around the machine is called its tune (ν)
  - ➪ The vertical/horizontal tune is the number of vertical/horizontal oscillations
  - ➪ The natural tunes for a given machine are defined by the arrangement and field strengths of the quadrupole magnets
  - ➪ They can be (and need to be) slightly different
    - ➔ Booster: $\nu_x = 6.7$ and $\nu_y = 6.8$

Instabilities Due to Field Errors

- Integer tunes are unstable w.r.t. dipole field errors

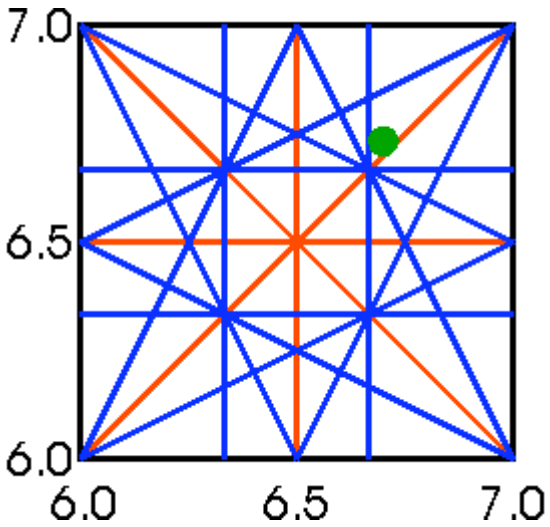


- Half integer tunes are unstable w.r.t. quadrupole field errors and so on ..



Instabilities Due to Field Errors II

- These instabilities are known as tune resonances
- In the general case tune values driven by resonances are given by : $m \nu_x + n \nu_y = k$
  - m, n, and k are integers
  - |m| + |n| is the order of the resonance
- Low order resonances are stronger than high order resonances



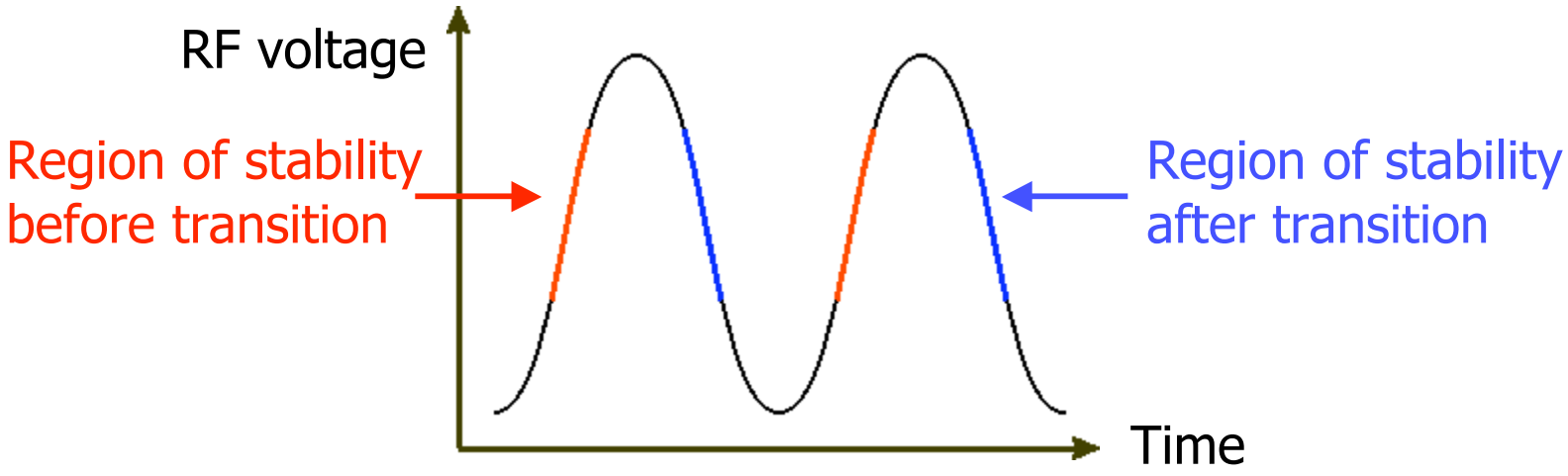
- 1st, 2nd, and 3rd order resonances are generally fatal
- Since the particles in the beam typically have different momenta they also have different tunes - tune spread
  - In order to avoid losses an accelerator needs to operate in a tune region which avoids all low order resonance lines.

Transition

- Higher momentum particles
  - Get bent less by the dipole magnets
  - Travel in larger radius orbits
  - Have higher velocities
- The path length differences remain constant as the beam momentum increases
- The velocity differences decrease as the particles become more relativistic
- Transition is the energy at which these two effects cancel
- Below transition high momentum particles reach the RF cavities 1st
- Above transition low momentum particles reach the RF cavities 1st

Transition II

- The RF phase has to be changed in order to maintain the beam in stable RF buckets
- The transition energy represents a point of instability in the acceleration cycle and is determined by the size of the ring and the strength of the magnets
  - ➪ For the Booster $K.E._{transition}$ = 3.26 GeV



Other Sources of Instabilities

- Wake Fields
  - Bunched beam represents an AC current
  - Induces delayed image fields on the walls of the beam pipe
  - Induced wake field can interact coherently with trailing bunches or trailing particles of the same bunch to produce coherent motion
  - Results in all kinds of bizarre resonances
- Space Charge
  - Electrostatic forces tend to blow the beam apart
  - Creates large momentum spread large tune spread losses
  - Effect is reduced at high energy due to lorentz contraction of E-fields

Conclusion

It’s a miracle that machines work at all!